A Polarization Technique for Mitigating Low-Grazing-Angle Radar Sea Clutter

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***Abstract*—Traditional detection schemes in conventional maritime surveillance radars may suffer serious performance degradation due to sea clutter, particularly in low-grazing-angle (LGA) geometries. In such geometries, typical statistical assumptions regarding sea clutter backscatter do not hold. Trackers can be overwhelmed by false alarms, while objects of interest can be challenging to detect. Despite several decades of attempts to devise a means of mitigating the effects of LGA sea clutter on traditional detection schemes, minimal progress has been made in developing an approach that is both robust and practical.**

To supplement work exploring whether polarization information might offer an effective means of enhancing target detection in sea clutter, MIT Lincoln Laboratory (MIT LL) collected a fully polarimetric X-band radar dataset on the Atlantic coast of Massachusetts Cape Ann in October 2015. Leveraging this dataset, MIT LL developed Polarimetric Co-location Layering (PCL), an algorithm that uses a fundamental polarimetric characteristic of sea clutter to retain detections on objects of interest while reducing the number of false alarms in a conventional single-polarization radar by as many as two orders of magnitude. PCL is robust across waveform bandwidths, pulse repetition frequencies, and sea states. Moreover, PCL is practical: It can plug directly into the standard radar signal processing chain.

***Index Terms*—false alarm mitigation, low grazing angles, polarimetry, radar, sea clutter.**

I. Introduction

Sea clutter poses unique challenges for maritime radars looking at near-horizontal incidence out to sea. In such low-grazing-angle (LGA) geometries, the typical probability distribution assumptions underlying conventional constant false alarm rate (CFAR) detection do not hold [1]. As a result, the false alarm rate of CFAR detectors may increase so dramatically that trackers may be inundated with spurious detections. False alarms on LGA sea clutter can look object-like and can persist for several seconds [2]. The false alarm problem becomes more prevalent for finer range resolution (higher bandwidth) waveforms. LGA sea clutter is also a temporally non-stationary and spatially inhomogeneous process [3], rendering statistical solutions to the CFAR-in-LGA-sea-clutter problem difficult to realize.

It is well-known that polarization filtering in optics is an effective means of mitigating glare. It is also well-known that polarization is an underutilized dimension of signal information in radar. This is particularly true for surveillance radars, the fully polarimetric variety of which is still largely experimental due to perceptions of their complexity and expense [1]. Yet, some prominent researchers have long thought that the key to mitigating LGA sea clutter lay in the polarimetric dimension [4], [5]. Much of the work on LGA sea clutter, even in the polarimetric regime, often relies upon impractical assumptions regarding the statistical nature of the clutter and/or of the target [6]–[8]. Even approaches that make the fewest such assumptions [9] have not been shown to be robust across radar and environmental parameters. This is due in part to the dearth of available data to support algorithm design and test: The only publicly available fully polarimetric dataset is the IPIX Radar dataset [10]. While it has helped fuel research in the problem space of radar detection in LGA sea clutter, the freely available IPIX data consists only of 30 m range resolution data over 14 range bins corresponding to 7 range resolution cells, one of which contains a single canonical point target (a foil-covered beach ball).

To explore whether radar polarimetry offers a practical means of robustly mitigating LGA sea clutter across a range of radar and environmental parameters, we stood up a fully polarimetric radar and collected a large dataset. We then utilized this dataset to devise and test algorithms that leveraged polarization to mitigate LGA sea clutter. Polarimetric Co-location Layering (PCL) is one result of this effort.

II. Four Eyes and the Point de Chene Dataset

Four Eyes is a transportable, fully polarimetric, X-band radar assembled largely from commercial-off-the-shelf components. Four Eyes is shown in Fig. 1. During the last week of October 2015, Four Eyes was stationed at a coastal test site on Massachusetts' Cape Ann overlooking the Atlantic Ocean. The radar antennas were situated at 32' above mean sea level, so all objects of interest on which data was recorded were at grazing angles of 2.12° (at the near point of the main lobe's intersection with the sea surface) or less. These objects included a point target in the form of a navigational buoy as well as several fishing and lobster boats. While Four Eyes was on site, the remnants of Hurricane Patricia moved through the region; hence, data was taken not only across a variety of object types, but in a range of environmental conditions.

Data was also recorded across a range of radar parameters. Linear frequency modulated waveforms spanning 4-400 MHz of bandwidth were used. All waveforms used the highest pulse repetition frequency (PRF) permitted by unambiguous range requirements (6250 Hz), thus enabling synthesis by

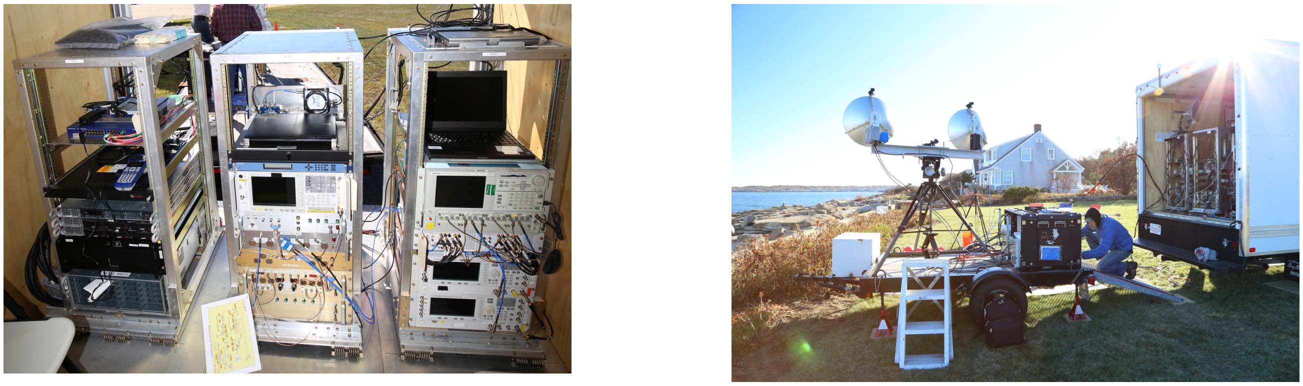

Fig. 1. Four Eyes X-band polarimetric radar is shown. At left, Four Eyes' data acquisition hardware is shown in the leftmost rack, its frequency generation and receiver hardware in the center rack, and it waveform generation and upconversion hardware in the rightmost rack. At right, Four Eyes is shown as installed in the box truck and on location in Massachusetts' Cape Ann. The radar's amplifiers and antennas are visible on the trailer behind the truck.

pulse decimation in post-processing of lower-PRF data. Additionally, all waveforms were transmitted in both alternating and simultaneous polarimetric schemes. The intent behind these choices was to enable characterization of algorithmic performance across a range of relevant radar parameters. These and other key parameters are summarized in Table I.

TABLE I
SELECTED RADAR AND DATA PARAMETERS

Four Eyes Polarimetric Radar	
Carrier frequency	9.705 GHz (X-band)
PRF	6250 Hz
Antenna polarizations	Dual-polarized linear (H and V)
Beamwidth	3.7°
Waveform bandwidths	4, 40, 150, 400 MHz
Polarimetric transmit schemes	Alternating, Simultaneous
Point de Chene Dataset	
Recording length	55 minutes
Total size	15.5 TB
Quasi-stationary objects	2 (Buoy, breakwater wall)
Moving objects	7 (Kayaker, fishing boats)
Douglas sea states	2, 3, 4, 5

III. POLARIMETRIC CO-LOCATION LAYERING

The goal of the algorithm development work for which the Point de Chene Dataset was subsequently leveraged was to find a means of leveraging polarimetric information to mitigate the impacts of LGA sea clutter on CFAR detection. Two performance standards also served to guide algorithm development work. First, an algorithm's performance should be robust across bandwidths, PRFs, and object types. Second, an algorithm should be able to incorporate directly into the standard radar signal processing chain without restructuring the existing chain or slowing down the chain's real-time performance. PCL is one result of our algorithm development work that achieves the goal while meeting the desired performance standards.

PCL works by leveraging a fundamental polarimetric characteristic of sea clutter that distinguishes sea clutter returns from returns due to man-made objects. Specifically, the sea surface features measured by horizontally polarized on transmit and receive (HH) radar have velocities that are different, on the average, from those measured by vertically polarized on transmit and receive (VV) radar. This differential average Doppler phenomenon was first discussed in [11]. Subsequent experiments showed that the differential average Doppler across HH and VV sea clutter is inversely proportional to grazing angle and proportional to sea state [12], observable to radar frequencies as high as W-band [13], and dependent upon look angle with respect to the wind. It is most pronounced when looking in the upwind and downwind directions as shown in Fig. 2, which is adapted from [1].

One result of this phenomenon is that CFAR detections on sea clutter in HH radar data move at different speeds across coherent processing intervals (CPIs) relative to CFAR detections on sea clutter in VV. However, the same is not true for detections on objects. If a point target has a signature in both the HH and VV measurements, then the object will have approximately the same radial velocity with respect to the radar in both polarizations; extended objects can be viewed as collections of point targets. PCL leverages these principles to filter out false alarms due to sea clutter while retaining detections on objects by

1) averaging pulses in a CPI in each of HH and VV;
2) performing CFAR detection on each averaged signal;
3) associating pairs of CFAR detections across HH and VV - i.e., *polarimetric co-location*; and
4) monitoring displacement of these pairs across a sequence of CPIs.

Pairs that move apart over time are deemed likely to be false alarms due to sea clutter and are filtered out of the detection set that is passed on to the radar tracker.

PCL performance is compared to standard single-polarization cell-averaging CFAR detection performance on

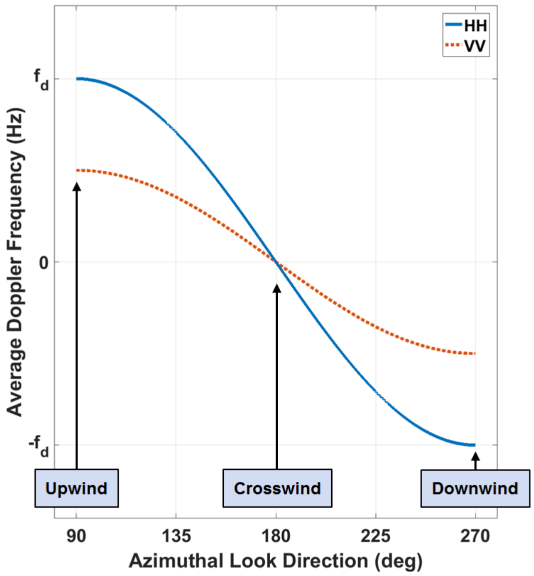

Fig. 2. The differential average Doppler across HH and VV co-polarizations is most pronounced when looking upwind and downwind. It goes to zero only when looking exactly crosswind.

TABLE II
PCL PERFORMANCE COMPARISON

			Mean p_{fa} (x 10^{-3})		
Objects	**β (MHz)**	**PRF (Hz)**	**HH CFAR**	**VV CFAR**	**PCL**
Buoy	**4**	6250	20.17	13.28	0
Buoy	**40**	6250	19.80	14.37	0.27
Buoy	**150**	6250	17.54	15.03	0.56
Buoy	**400**	6250	18.01	17.37	0.55
Buoy	4	**∼893**	26.54	21.89	1.16
Buoy	40	**∼893**	15.41	11.43	0.02
Buoy	150	**∼893**	17.75	14.18	0.46
Buoy	400	**∼893**	14.76	14.76	0.57
Boat #1	40	6250	21.86	16.91	0.56
		∼893	12.63	10.40	0
Boat #2	150	6250	19.49	16.35	3.92
		∼893	14.63	11.82	0.67
Two Boats	400	6250	14.67	14.33	1.56
		∼893	10.56	10.63	0.40

several files from the Point de Chene Dataset in Table II. The CFAR false alarm rate (p_{fa}) in each of these cases was set to 10^{-6}. The actual mean p_{fa} for both HH and VV CFAR exceeds the desired rate by three orders of magnitude due to sea clutter. By leveraging both polarizations using PCL, these false alarm rates are reduced by an average of two orders of magnitude. Though not shown, PCL maintains detection on all objects in these files. As the table reflects, PCL's performance is robust across bandwidths, PRFs, and object types in the Point de Chene Dataset. Moreover, PCL can be incorporated into the standard radar signal processing chain in parallel with the usual Doppler processing and 2-D CFAR operations, and as shown in [14], PCL executes faster than the operations with which it runs in parallel.

IV. Conclusions

PCL is a novel algorithm that leverages polarimetric radar and a fundamental characteristic of sea clutter to mitigate the impacts of LGA sea clutter. PCL is robust across the bandwidths, PRFs, and object types in the X-band Point de Chene Dataset and can be incorporated into the standard radar signal processing chain without slowing down radar performance. Because PCL requires only linear co-polarized measurements, PCL can run in any radar capable of measuring HH and VV.

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References

[1] K. D. Ward, S. Watts, and R. J. A. Tough, *Sea Clutter: Scattering, the K Distribution, and Radar Performance*, IET, 2006.

[2] S. Watts, "Radar sea clutter: Recent progress and future challenges," *2008 IEEE International Conference on Radar*, pp. 10–16, 2008.

[3] M. Greco, F. Gini, A. Younsi, M. Rangaswamy, and A. Zoubir, "Non-stationary sea clutter: impact on distubance covariance matrix estimate and detector CFAR," *2008 IEEE International Conference on Radar*, pp. 558–562, 2008.

[4] S. Haykin, E. O. Lewis, R. K. Raney, and J. R. Rossiter, *Remote Sensing of Sea Ice and Icebergs*, John Wiley & Sons, 1994.

[5] M. W. Long, *Radar Reflectivity of Land and Sea*, 3rd Edition, Artech House, 2001.

[6] G. Wanielik and D. R. Stock, "Measured scattering-matrix-data and a polarimetric CFAR-detector which works on this data," *Record of the IEEE 1990 International Radar Conference*, pp. 514-519, 1990.

[7] A. De Maio and G. Alfano, "Polarimetric adaptive detection in non-Gaussian noise," *Signal Processing*, vol. 83, no. 2, pp. 297–306, 2003.

[8] H. R. Park and H. Wang, "Adaptive polarisation-space-time domain radar target detection in inhomogeneous clutter environments," *IEE Proceedings on Radar, Sonar, and Navigation*, vol. 153, no. 1, pp. 35–43, 2006.

[9] M. Hurtado and A. Nehorai, "Polarimetric detection of targets in heavy inhomogeneous clutter," *IEEE Transactions on Signal Processing*, vol. 56, no. 4, pp. 1349–1361, 2008.

[10] S. Haykin, R. Bakker, and B. Currie, *The McMaster IPIX Radar sea clutter database - Dartmouth 1993*, [Online]. Available: http://soma.ece.mcmaster.ca/ipix/dartmouth/index.html 2001, Accessed: 2015-01-28.

[11] V.W. Pidgeon,"Doppler dependence of radar sea return," *Journal of Geophysical Research*, vol. 73, no. 4, pp. 1333–1341, 1968.

[12] G.R. Valenzuela and M.B. Laing, "Study of Doppler spectra of radar sea echo," *Journal of Geophysical Research*, vol. 75, no. 3, pp. 551–563, 1970.

[13] T. Lamont-Smith, "Doppler spectra of laboratory wind waves at low grazing angle," *Waves in Random and Complex Media*, vol. 10, no. 1, pp. 33–41, 2000.

[14] M.K. Crane, "Polarization Techniques for Mitigation of Low Grazing Angle Sea Clutter." Ph.D. Dissertation, Boston University, 2017.